# *Development of Bi-Modal Fuels for Nuclear Thermal Propulsion and Power*

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Nov 19, 2014

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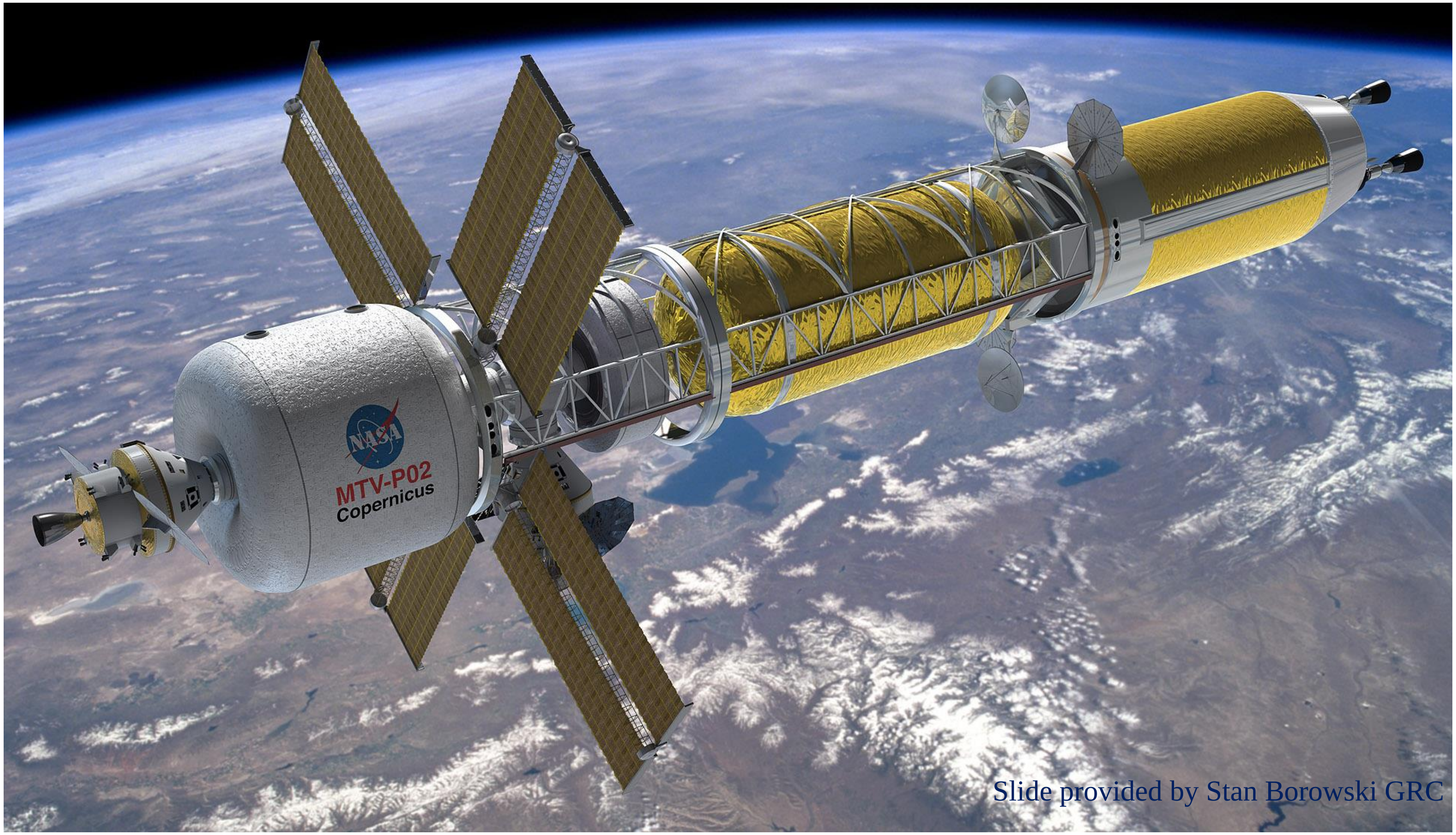
Idaho National Laboratory

20th Advanced Space Propulsion Workshop

***Mankind is drawn to the heavens for the same reason we were once drawn into unknown lands and across open seas. We choose to explore space because doing so improves our lives, and lifts our national spirit. So let us continue the journey. - G.W. Bush***



# *Outline*

- Thermal Nuclear Propulsion
- Nuclear Power
- The challenges to designing a bi-modal reactor?
- HTGR fuel development
- What are options and steps forward
- Conclusions

# Why Nuclear?

- **Provides enormous fuel energy density**


**Fission** = 50 x

**Radioisotope** =

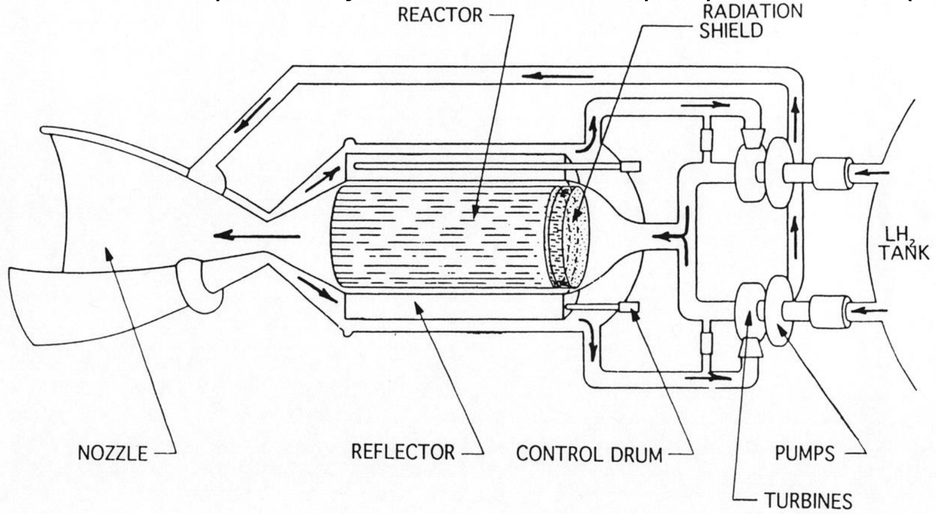
- **Overcomes limitations of other candidate power sources**
  - Not dependent on location w/respect to sun or planet
  - Operates in shadows or at night
  - It is a technology that <u>is ready today</u>

- **Improves safety and capability of future human or science missions**
  - Power-rich environment
  - Potential for rapid transportation

# NTP Basics

### Solid Core Nuclear Thermal Rocket Engine Schematic

*Expander Cycle, Dual LH2 Turbopump Assemblies (TPA)*




| **Typical Attributes:** | LOX/$LH_2$ | NTP |
|---|---|---|
| Specific Impulse | *420–460 s* | ***800–900 s*** |
| Thrust/Weight | *50–70* | *3–6* |
| Exhaust Temperature | *>3000 K* | *2300-2900 K* |

## Benefits:

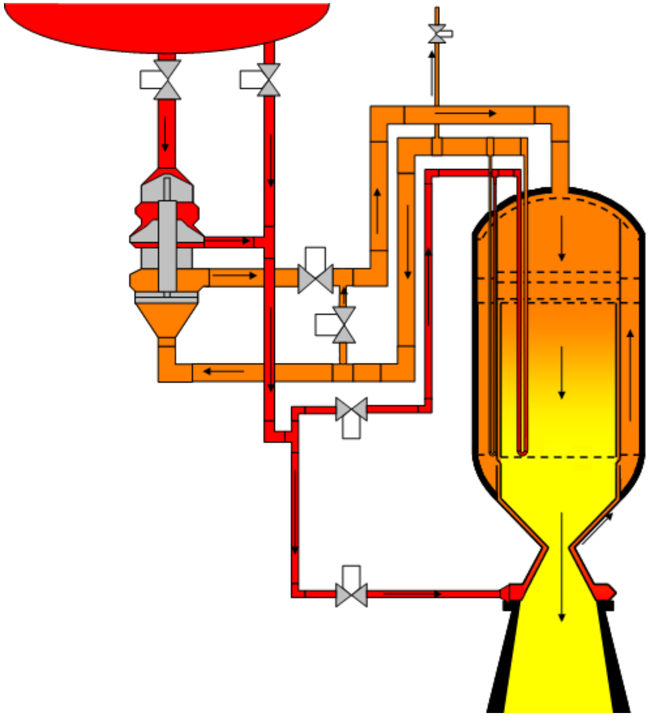
- Reduced launch mass or trip time due to twice the specific impulse of chemical propulsion
- Increased mission launch opportunities
- Experience from previous programs
- Leverages chemical rocket experience
- Scaleable – no combustion instability

## Challenges:

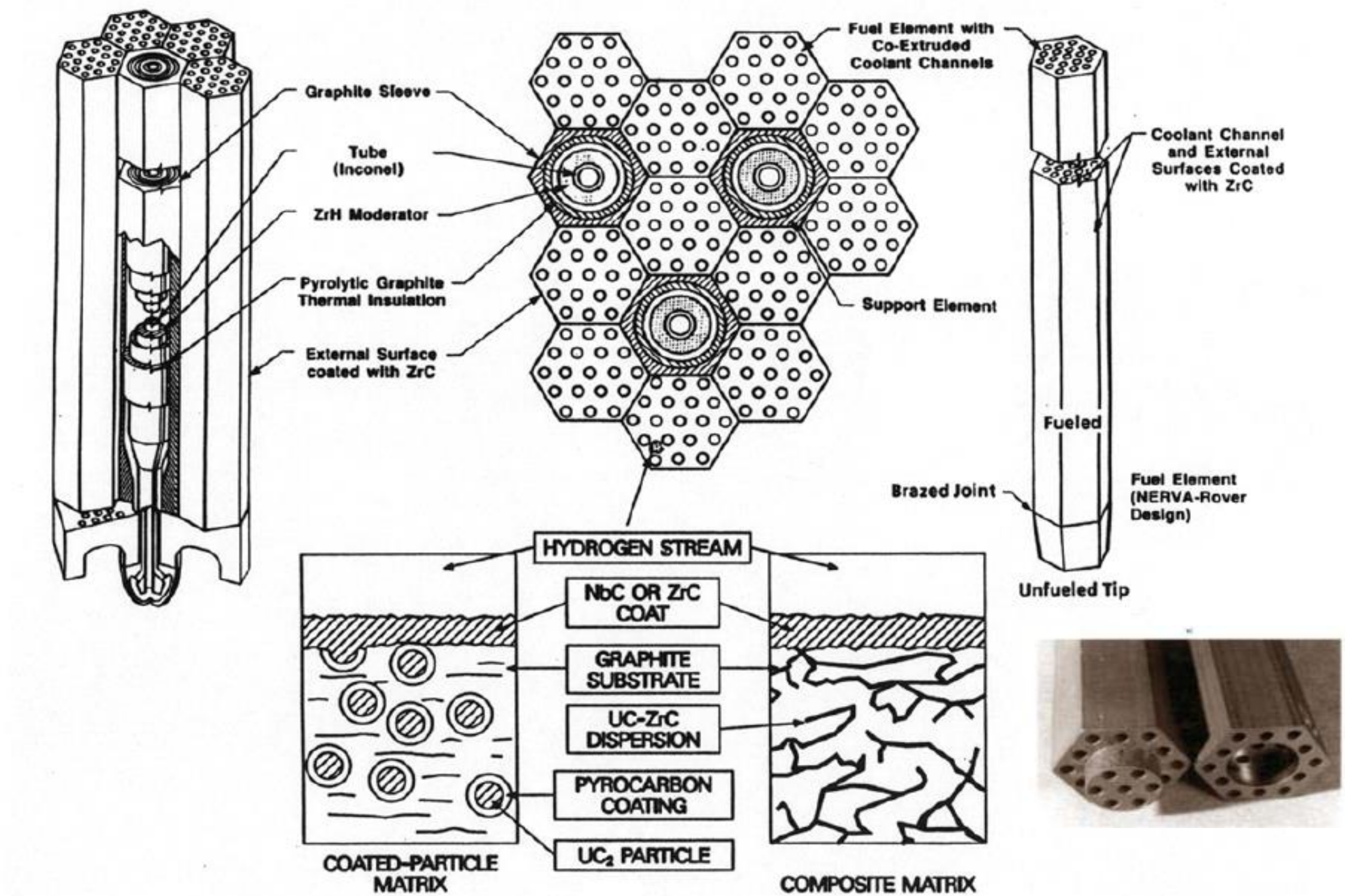
- Nuclear fuel recapture/development
- Cost of required ground test facilities
- Human-rating qualification
- High launch volume $LH_2$ propellant
- Cryogenic fluid management (CFM)

# NTR System Properties

- Propellant / Coolant - Hydrogen
- Peak Fuel Temperature – 2860 K
- Chamber Temperature – 2790 K
- Chamber Pressure – 1000 psia
- Reactor Power - 550 MWth
- Design Thrust – 25 klbf
- Specific Impulse - 900 s
- Thrust-to-weight – 3.42

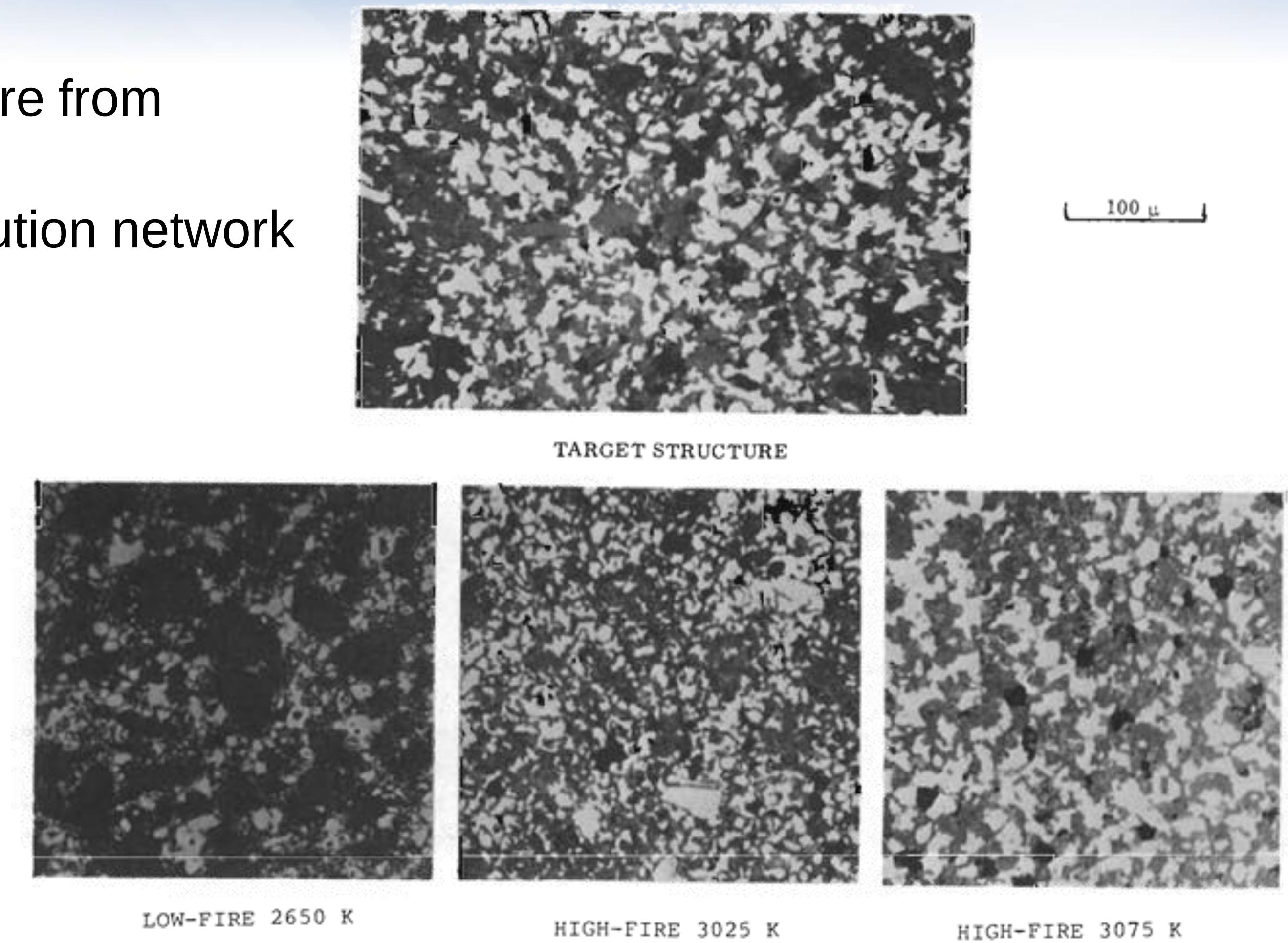


# "Heritage" Rover / NERVA Composite Fuel Element and Tie Tube Bundle Arrangement



# Heritage Composite Microstructure

- Target microstructure from literature
- Consist of solid solution network of ZrC



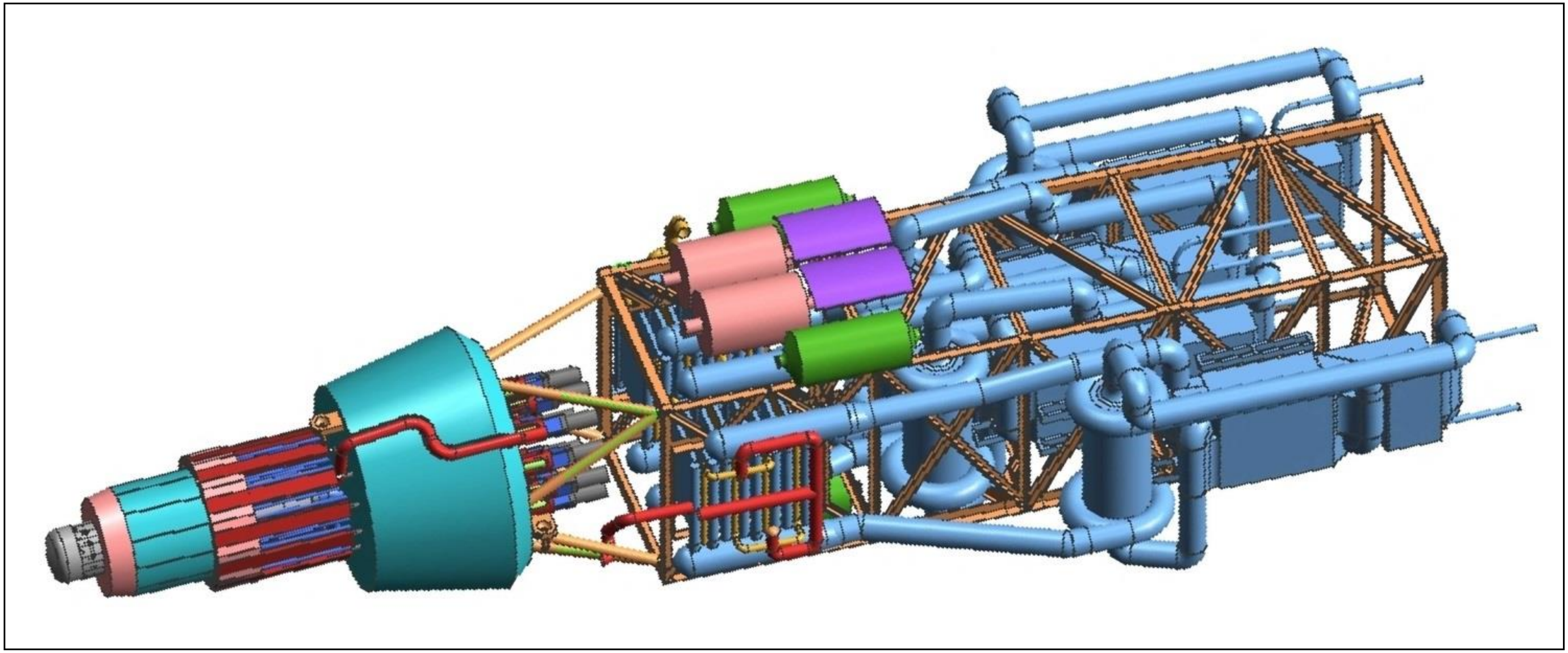

ELEMENTS FROM LOT 62 (KX-88, 35 vol%, 382 kg U/$cm^3$) (STATION 28)

Fig. B2. Microstructure of composite elements as a function of heat-treatment temperature. The gray areas are graphite, the white areas are carbide, and the black areas are void.

# *NTR Fuel*

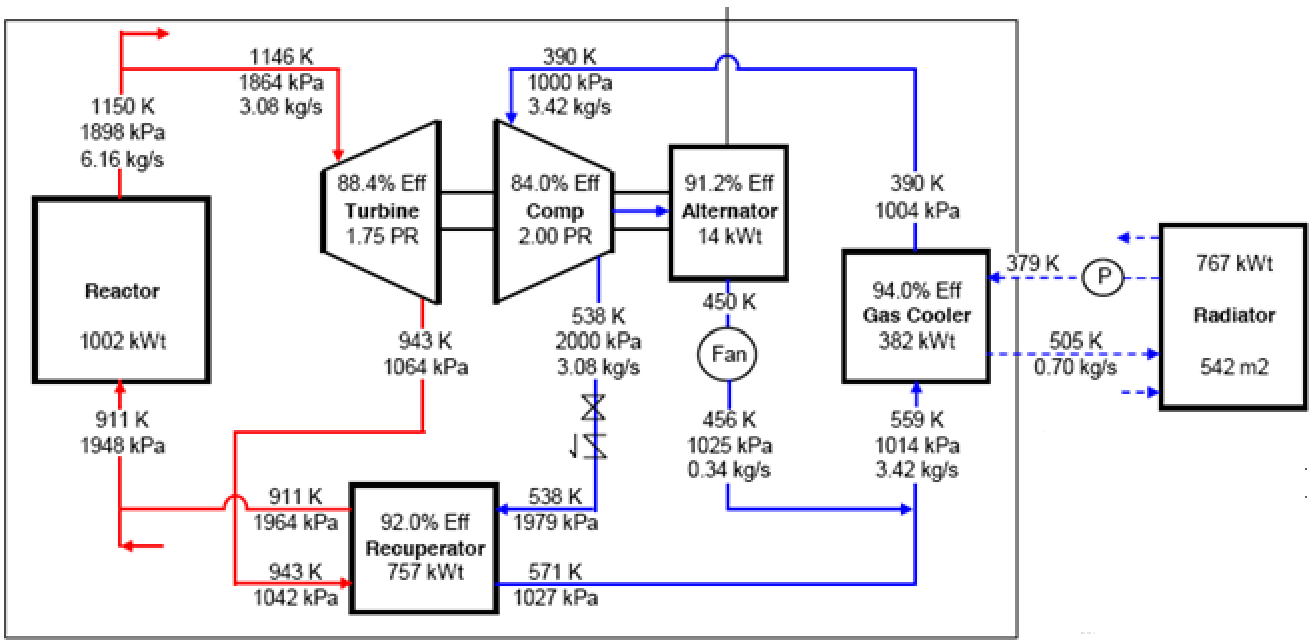
- Challenges
  - High temperatures near melting point of fuel and materials
  - Plastic deformation
  - Uranium migration
  - High pressures
  - Hydrogen erosion causing loss of cladding and fuel
- Advantages
  - Very little fuel consumed
  - Very little fission products generated
  - Operates for 120 minutes

# Nuclear Power



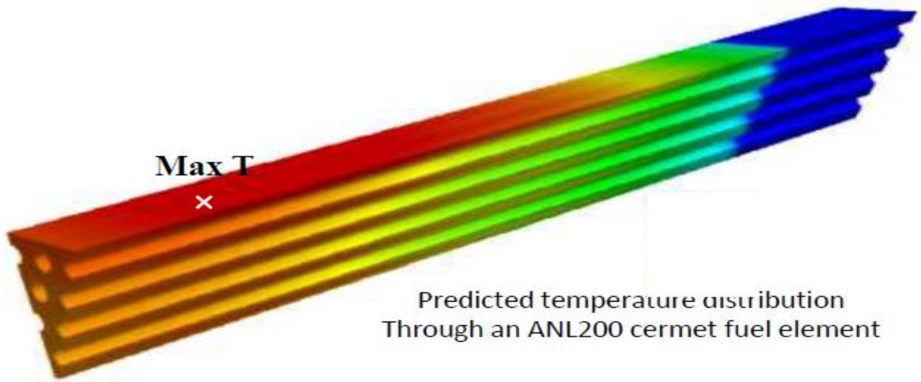
# NP System Properties

- Coolant – He, LM, HP
- Peak Fuel Temperature – 1200 K
- Pressure – 1000 to atm psia
- Reactor Power – 1000 -120 kWth



# Melting Points of Reactor Fuels/Materials

| Material/ Element | Melting Temperature (K) (No $H_2$) |
|---|---|
| UC | 2805 |
| $UC_2$ NERVA Peewee | 2835 |
| UC-40 ZrC NERVA Composite | 3050 |
| $(U_{0.1}Zr_{0.9})C_{0.96}$ | 3550 |
| $(U_{0.1}Zr_{0.9})C_{0.98}$ | 3100 |
| W-60 v/o $UO_2$ Cermet | 3075 |
| Uranium Nitrides | Chemically Unstable |
| Tungsten | 3687 |
| Graphite | 3915 (sublimes) |
| ZrC | 3805 |




Predicted temperature distribution
Through an ANL200 cermet fuel element

$$T_{fuel\_max} - \Delta T_{safety} - \Delta T_{matrix} \cong T_{propellant}$$

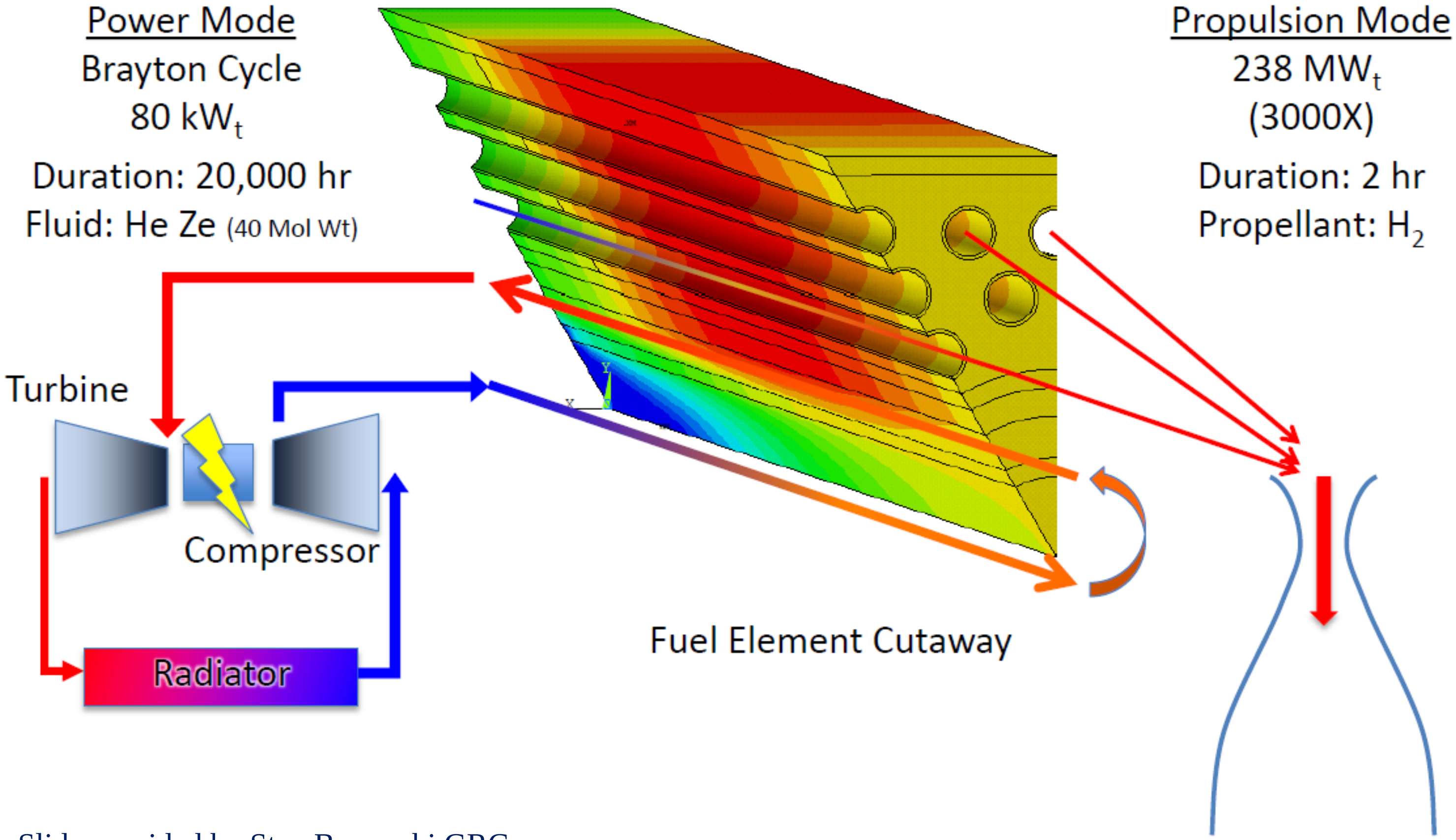
| Design | $\Delta T_{matrix}$ (K) |
|---|---|
| NERVA SNRE | 220 (130) |
| Cermet ANL200 | 520 (500) |
| Cermet GE710 | 140 |

Slide provided by Stan Borowski GRC

# Bimodal Operations For NTP

<u>Power Mode</u>
Brayton Cycle
80 $kW_t$
Duration: 20,000 hr
Fluid: He Ze (40 Mol Wt)

<u>Propulsion Mode</u>
238 $MW_t$
(3000X)
Duration: 2 hr
Propellant: $H_2$




Fuel Element Cutaway

Slide provided by Stan Borowski GRC

# NP Options

- Use of heat pipes in reflector
- Coolant channels in reflector or control drums
- Use of tie-tubes in core attached to power generation system

# What are the Challenges

**Propulsion**

- High Temperature (2300 C)
- Short operation (min)
- Low FP interaction
- Open cycle
- Affect of long term operation on restart and burn times

**Power**

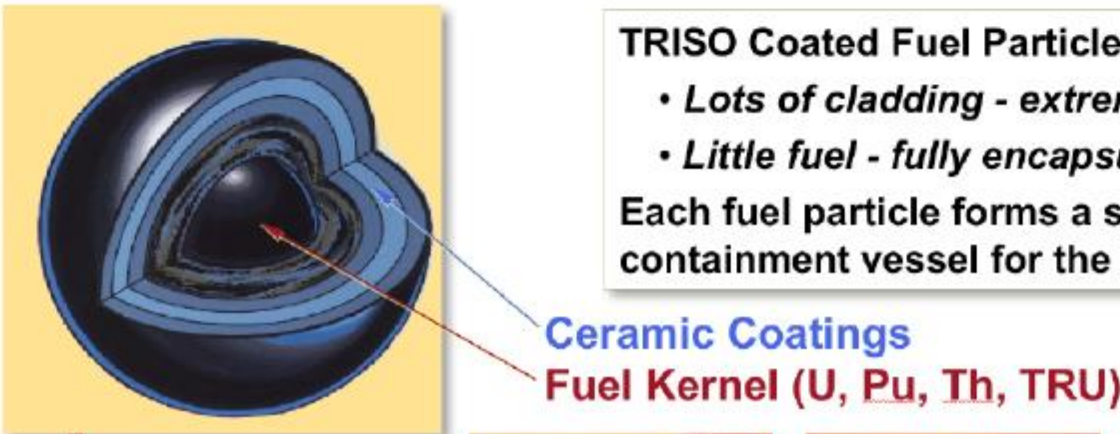
- Moderate temperature (700 C)
- Long operation (yr)
- FP interaction with fuel and cladding
- Closed cycle
- Ability to survive NTR operation
- Impact on NTR operation

# *High Temperature Gas Reactor*

TRISO Coated Fuel Particles:

- *Lots of cladding - extremely strong*
- *Little fuel - fully encapsulated*

Each fuel particle forms a separate pressure containment vessel for the kernel (to 1000 atm)





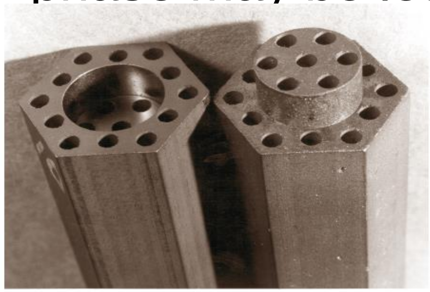
*Prismatic concept illustrated - Pebble Bed variant also possible*

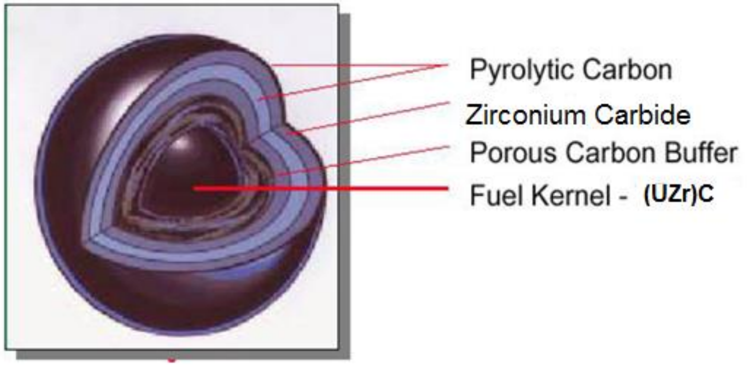
# *Options for Developing Bi-Modal Fuel*

- Step 1
  - Test composite fuel currently being developed at ORNL
  - Operate at lower temperatures
  - Analyze for long duration operating times
    - Fuel / Cladding interactions
    - FP interactions
    - Uranium migration
  - Analyze stresses due to temperature transients
  - Model / optimize core configurations

# Options for Developing Bi-Modal Fuel

- Step 2
- Investigate HTGR particle fuel using advanced coating and QC techniques
  - (Uzr)C kernal allows for high temperature operation
  - Zirconium Carbide outer layer provides protection from hydrogen
- Buffer layer around the fuel will allow for retention of fission products during power operation
- Because of the multi layers operating temperature during propulsion phase may be less, but fits in well with existing designs





# *Other Design Options*

- Cermet fuel – with heat pipes- UO2W cermet fuel
- Liquid fueled annular reactor – interior core is liquid for propulsion, coolant loops in the reflector for power $UC_2$ (molten)
- Particle bed reactor – closed loop tie-tubes for power and turbine pump Hydrogen flows through particle bed (outer frit to inner frit) for propulsion.   400-500 micron $UO_2$ with multi-layer coatings.

# Conclusions

- Continue development of NTR composite fuel
  - Verify fabrication and performance characteristics
  - Conduct additional reactor experiments and modeling to understand performance characteristics for power
- Investigate particle fuel for NTR options
  - Utilize advances in fuel fabrication
  - Perform trade studies to find optimum balance between NTR and NP options
- Development of one fuel for multiple applications is the preferred option